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Wind waves on the surface of the sea are modulated by both longer waves (e.g., swell) and by low frequency motion such as Langmuir circulation or internal waves. The modulation of the small wind wave components helps to make the lower frequency activity "visible," both with optical and radar techniques. Conversely, the interaction with the larger wind waves can be important to the formation and growth of the low frequency motion. The growth and dissipation of the surface waves are also important in this interaction. Mean rates of growth (and, by implication, dissipation) of the waves as a function of wind, stability, etc. are fairly well known.

The ultimate goal is to understand the physical mechanisms behind observed modulations of surface wind waves. Proper interpretation of remotely sensed images require a thorough understanding of the behavior of the short scattering waves. In addition, estimates of air-sea fluxes of gases, heat, momentum, etc. are strongly dependent on the details of the wave modulation and breaking, both directly and via induced "secondary flows" such as Langmuir circulation.

This project addressed two problems within this rather broad context: first, the modulation of short waves by longer ones, in the presence of both strong generation and dissipation; second, the interaction of surface waves and Langmuir circulation, with special attention towards identifying an observable effect on the waves.

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Project Report: Interaction of surface waves and near-surface currents.

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Introduction

Wind waves on the surface of the sea are modulated by both longer waves (e.g., swell) and by low frequency motion such as Langmuir circulation or internal waves. The modulation of the small wind wave components helps to make the lower frequency activity "visible," both with optical and radar techniques. Conversely, the interaction with the larger wind waves can be important to the formation and growth of the low frequency motion. The growth and dissipation of the surface waves are also important in this interaction. Mean rates of growth (and, by implication, dissipation) of the waves as a function of wind, stability, etc. are fairly well known. However, a more detailed knowledge of where and when waves dissipate is required to assess properly the impact on, e.g., formation of Langmuir circulation, entrainment of bubbles into the mixed layer, and the visible signature of "slicks". An important factor influencing wave dissipation is the near-surface "wind drift layer", which is itself modulated by the underlying flow.

The ultimate goal is to understand the physical mechanisms behind observed modulations of surface wind waves. Proper interpretation of remotely sensed images require a thorough understanding of the behavior of the short scattering waves. In addition, estimates of air-sea fluxes of gases, heat, momentum, etc. are strongly dependent on the details of the wave modulation and breaking, both directly and via induced "secondary flows" such as Langmuir circulation.

This project addressed two problems within this rather broad context: first, the modulation of short waves by longer ones, in the presence of both strong generation and dissipation; second, the interaction of surface waves and Langmuir circulation, with special attention towards identifying an observable effect on the waves.

Background

In the past two decades, an effective framework for the study of surface waves in a "slowly varying" environment has evolved, based on the conservation of wave action (Bretherton and Garrett 1968; Garrett 1976). The concept of wave action itself has become better defined, and the conditions for its conservation have been expanded considerably. Whitham (1974) showed that, to second order, action is conserved for a wide class of problems even without the "slowly varying" constraint, as was confirmed (for example) in the case of waves crossing a vortex sheet (Evans 1975) or a pair of vortex sheets (Smith 1983). A quantity was defined by Andrews and McIntyre (1976) which reduces to the "standard" form for action at second order, and which is exactly conserved. These theoretical assurances, combined with the simplicity of its application, have made action conservation a powerful tool in studying the interactions between waves and thier environment. This has been the primary tool of investigation in this work.

Modulation of short surface waves

Previous work on the modulation of short waves by long ones focussed first on the "conservative" interaction (i.e., with no wind forcing or dissipation; e.g., Longuet-Higgins and Stewart 1964). Then some relatively simple models were introduced to assess the impact of growth and dissipation on the modulation of the short waves, and in some cases the back-effect on the long waves (Keller and Wright 1976, Garrett and Smith 1976, Hughes 1978, Valenzuela and Wright 1976 and 1979, etc.). Just prior to the present work, a "dissipative balance" for surface

waves modulated by a larger scale flow was developed, and applied to short waves modulated by longer ones (Smith, J.G.R. 1986). The most significant unknown or ill-known parameters were identified as (1) the modulation of input from the wind, (2) the modulation of the turbulent wind-drift layer, and (3) the resulting modulation of the dissipation of the waves.

As in the immediately preceding work, the observations of wave modulations were used to narrow down the description of these ill-known physical processes. The turbulent roughness scale in the wind-drift layer was "updated" to include the case $z_0 \propto w_*^2$, and this performs as well as any of the previously published versions, in addition to being consistent with the form observed on the atmospheric side of the boundary. A new aspect of this investigation was to reconsider the response characteristics of the wind drift layer to a varying shear stress. The results of the model are less sensitive to the form of roughness variation than they are to this response time of the drift layer. The results are roughly consistent with the observations, provided that the time-scale for evolution of the wind-drift is comparable to that of the waves; considering longer waves implies including a thicker layer, with a correspondingly longer response time. In addition, as before, the variations in shear-stress transmitted across the interface are inferred to be large, completely dominating the results. Thus, a major conclusion of the work is that the results are most strongly dependent on the ill-known variations in the turbulent shear layers, both in the air and in the sea (Smith 1990).

The long-wave short-wave interaction has been a good "testing ground" for the dissipation model of the waves, and for the behavior of the wind drift layer under varying forcing. The underlying approach was to linearize with respect to "small" perturbations about a statistically steady state. To carry the long-wave short-wave problem farther than this would entail development of a non-linear model of the co-evolution of the waves and the boundary layers in the air and sea. While this is feasible, it constitutes a rather different sort of research than that conducted so far. A more logical progression is to take the theoretical framework as developed and apply it to a similar problem, such as the interaction of surface waves with internal waves and/or Langmuir circulation. Equally compelling, a field research program was being carried out, addressing precisely these issues: measurement of surface waves, internal waves, and mixed layer flow. In view of this, it was felt that extension to non-colinear wave systems is not yet warranted, and so the second half of the project was diverted towards investigation of the interaction between waves and Langmuir circulation.

Waves and Langmuir circulation

The generation of Langmuir circulation as an instability due to the interaction of waves and wind-induced shear is now well accepted (Craik and Leibovich 1976, Garrett 1976, Leibovich 1983, etc.). However, there remain some unresolved questions. A lowest order question is whether there is some observable effect by which it can be verified that the mechanism is "working" in the ocean. An early hypothesis that the waves are larger within the "streaks" (surface convergence zones) of Langmuir circulation has been more or less discredited by both theoretical analysis (Smith 1980, 1983) and observations (Smith 1980). Also, the mechanism finally outlined by Craik and Leibovich produces reasonably large growth rates for the circulation, even without such "direct reinforcement."

It is a little appreciated fact that the mechanism finally proposed by Craik and Leibovich has a simple connection with that proposed by Garrett (1976): The "primitive" version of the effect of the waves on the flow yields the CL mechanism by taking its curl, while Garrett's formulation results from vertical integration (see, e.g., Leibovich 1980, Smith 1980). This results in a "wave force" directed along the surface toward the maximum in downwind current (in Garrett's terminology, $M \times (\nabla \times U)$, where M is the wave momentum and U is the downwind current). The two approaches have complementary attributes: the CL formulation reveals the vertical structure of

the forcing, which is important to the development of the circulation, while Garrett's formulation indicates a way to approach the variation of the wave-field due to the interaction.

In an earlier analysis (Smith 1983), I was able to show that reflections and interference with reflections across a narrow jet effectively cancel the variations in wave height suggested by Garrett (1976). However, net action flux is still constant, and at any point across the current pattern, the waves retain a form very close to that of a "locally plane" wave. So, provided (partial) reflections are properly accounted for, the basic approach of ray tracing combined with action conservation can still be applied, even though the scale of the current is not necessarily "small" compared to the wavelength.

The primary result of this project lies in showing a direct relation between the strength of the "wave force" and detectable variations in the magnitude of the crosswind component of wave orbital velocities. For Langmuir cells with the typical strengths reported in the literature, and with a reasonable directional spread of surface waves, the total crosswind orbital variance should vary across the cell by as much as 30%, with larger fractional variations for higher frequency wave components. This should be easily detectable with our surface scanning Doppler sonar systems, and indeed preliminary looks at the data recently gathered for SWAPP (Feb. and March 1990) show some evidence of its existence. In view of this, the analysis will be published (hopefully) in conjunction with data.

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